MODEL VALIDATION FOR SIMULATIONS OF VEHICLE SYSTEMS

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GVSETS

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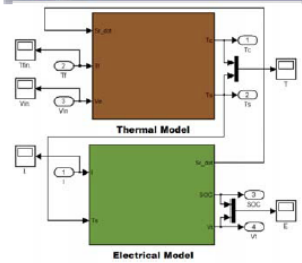
VV&A

- Verification
  - Is the mathematical model solved correctly?
- Validation
  - Is a model adequate in representing the “real” physical system?
    - Contextual process
    - Subjective results
    - Various types of model outputs
- Accreditation
  - Can a model be exercised within a well-defined scope?

Models of Dynamic Systems

Single Cell – ElectroThermal Model



- **Inputs**
  - I (Current)
  - Tf (Inlet Air Temp)
  - Vin (Inlet Flow Velocity)
- **Outputs**
  - Tc (Core Temperature (ºC))
  - Ts (Surface Temperature (ºC))
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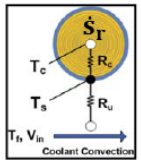
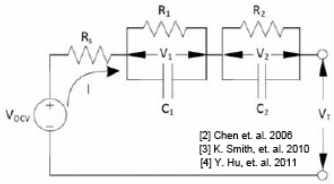
  - SOC (State of Charge)

- **Thermal Model**
  - Two States (Tc, Ts)
  - Two Inputs (Tf, Vin)



[5] C. Park, et. al. 20
[6] X. Lin, et. al. 201
[7] X. Lin, et. al. 201

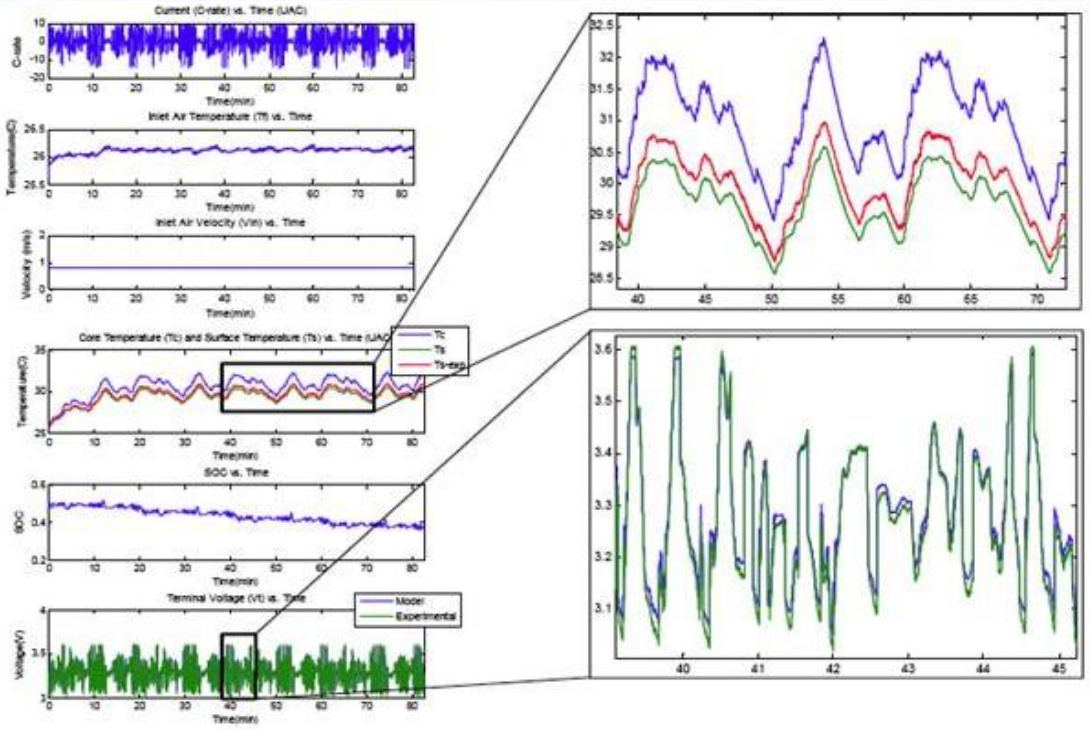
- **Electrical Model: OCV-R-RC**
  - Three States (SOC, V1, V2)
  - One Input (I)



[2] Chen et. al. 2006
[3] K. Smith, et. al. 2010
[4] Y. Hu, et. al. 2011

- Multiple, time-dependent output

UAC Experimental vs. Simulation Results

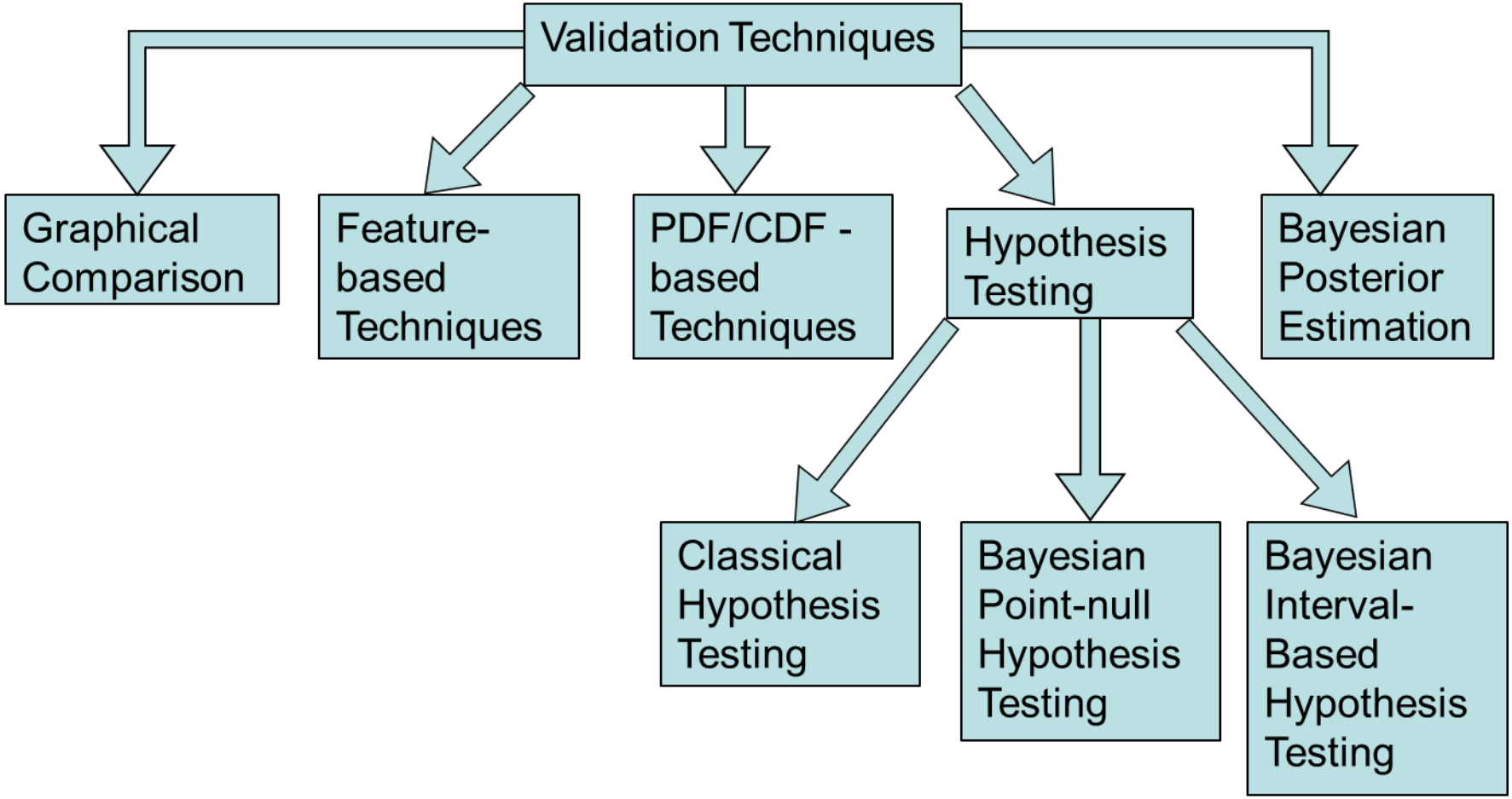


- Entire time history matters, not just some of its features

Outline

- Classification of validation approaches
- Bayesian interval hypothesis testing
  - Quantifying model confidence
  - Distribution-free approach by means of bootstrapping
  - Statistical power superiority
- Validation benchmark problem
- ARC-developed electro-thermal battery model validation for energy & power community of interest application

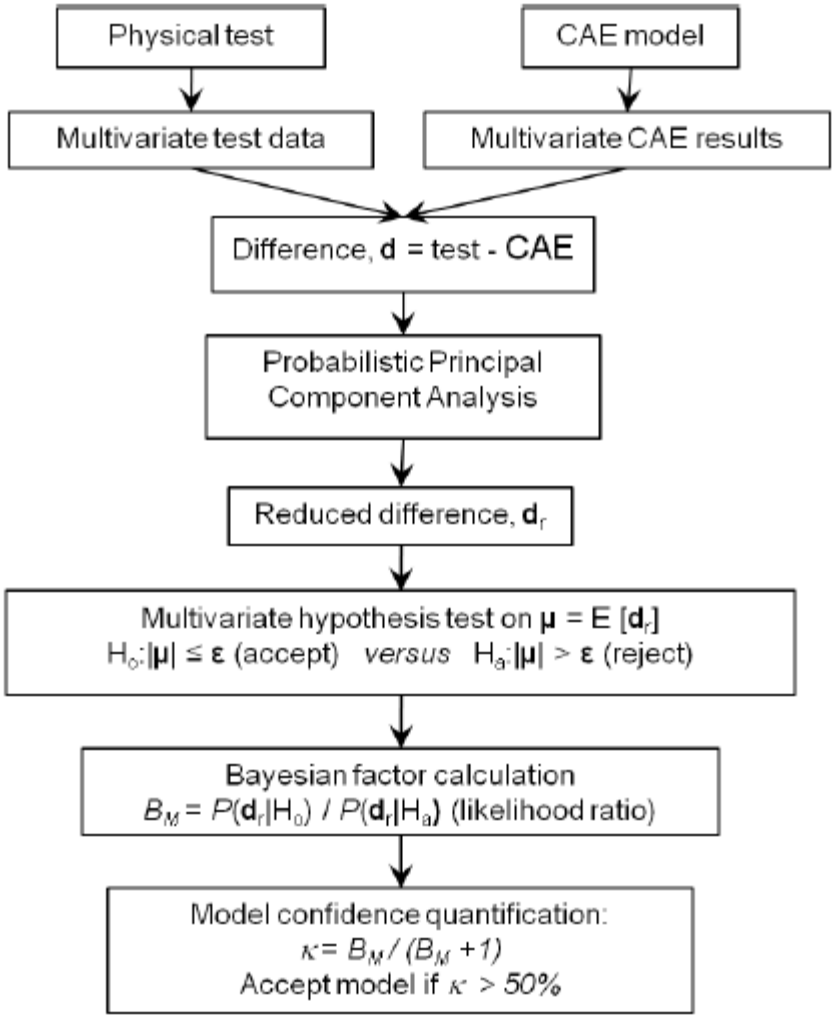
Classification of validation methodologies



Attributes of validation methodologies

	Graphical comparison	*Feature-based methods*	*PDF/CDF-based methods*	*Classical hypothesis testing*	*Bayesian hypothesis testing (point-null)*	*Bayesian hypothesis testing (interval-based)*	*Bayesian posterior estimation*
Applicable to scalar data	No	Yes	Yes	Yes	Yes	Yes	Yes
Applicable to vector data	No	No	Yes	Yes	Yes	Yes	Yes
Applicable to scalar time series	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Applicable to vector time series	Yes	No	Yes	Yes	Yes	Yes	Yes
Consider multivariate correlation	No	No	No	Yes	Yes	Yes	Yes
Include objective criteria	No	No	No	Yes	Yes	Yes	No
Quantify model confidence	No	No	No	No	Yes	Yes	No
Can incorporate SME opinions	Yes	Yes	No	No	Yes	Yes	Yes
Can work without normality assumption	Yes	Yes	Yes	No	Yes	Yes	No
Insensitive to type-I error	Yes	Yes	Yes	No	Yes	Yes	Yes
Low computational cost	Yes	Yes	Yes	Yes	No	No	No
Sample size independence	Yes	Yes	No	No	No	Yes	Yes

Bayesian hypothesis testing



Zhan, Fu, Yang, Peng (2011)

Norm-based integration bounds

- Sensitivity of model confidence

$$K = \int_{-\varepsilon}^{+\varepsilon} \frac{1}{\sqrt{2\pi\sigma^2}} exp\left[-\frac{n+1}{2\sigma^2}\left(\mu - \frac{n}{n+1}\bar{d}_r\right)^2\right] d\mu$$

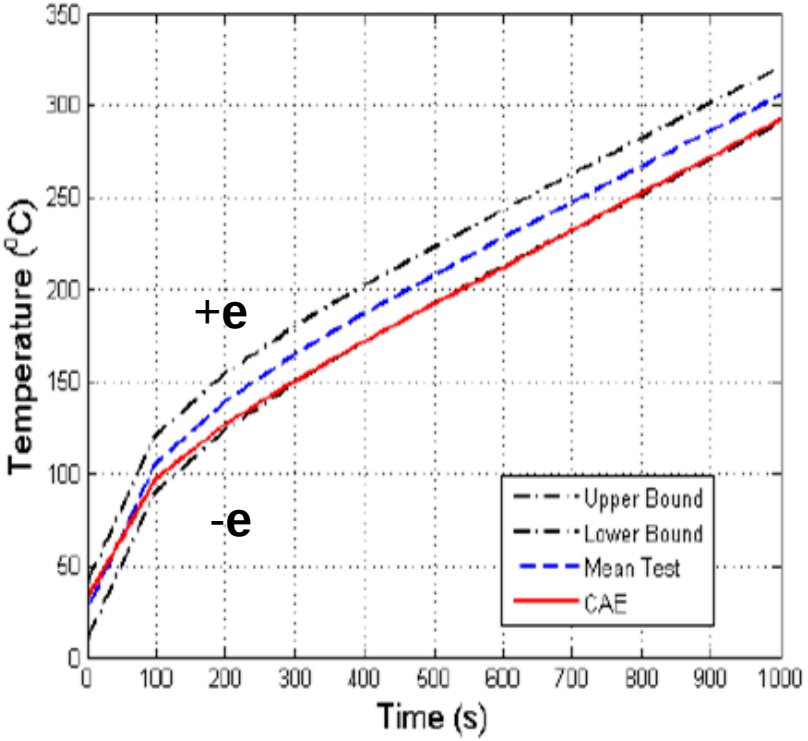
- Based on intended application/ SME opinions

$$\mathbf{e} = b\|\mathbf{t}\|_\infty$$

- Fit in the Bayesian model validation framework

$$\boldsymbol{\varepsilon} = abs\left(\mathbf{M}^{-1}\tilde{\mathbf{W}}^{\mathrm{T}}\mathbf{e}\right)$$

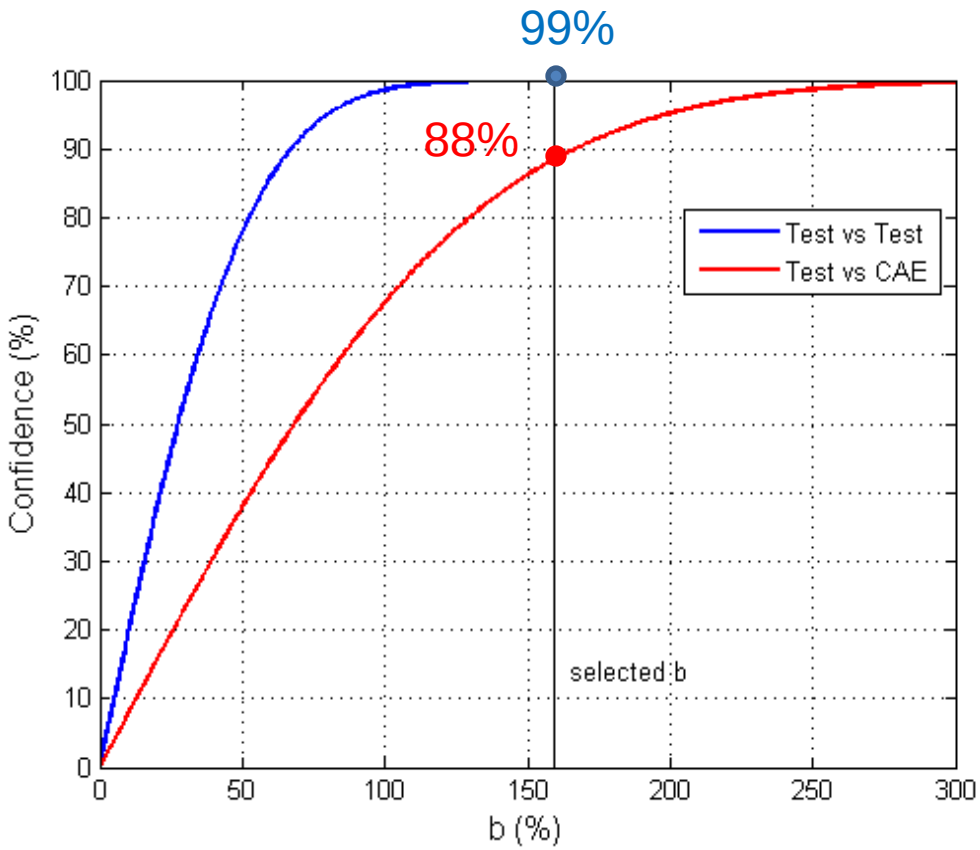
Example of norm-based integration bounds



Variability-based integration bounds

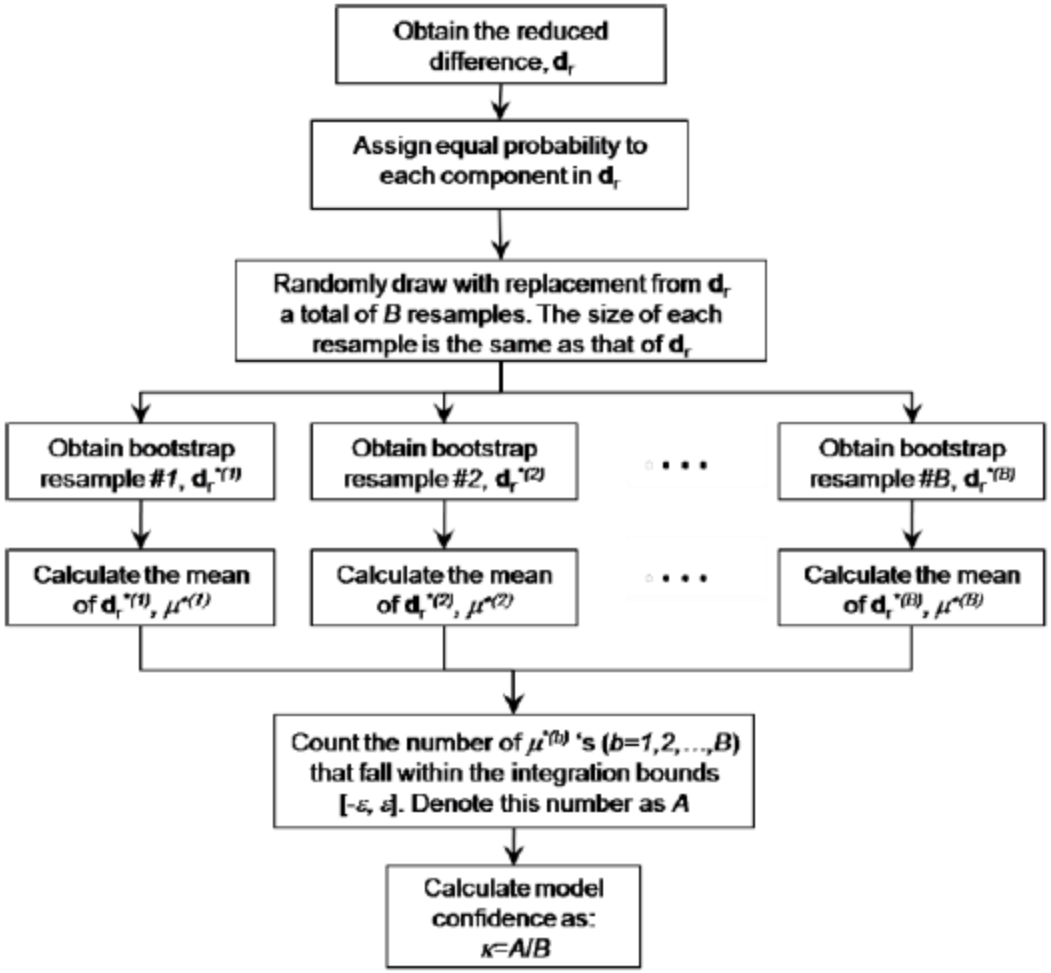
- What confidence should one expect when comparing test data with themselves?
- Based on standard deviation of the reduced test data

$$\boldsymbol{\varepsilon} = b\sqrt{diag(\boldsymbol{\Sigma}_t)}$$



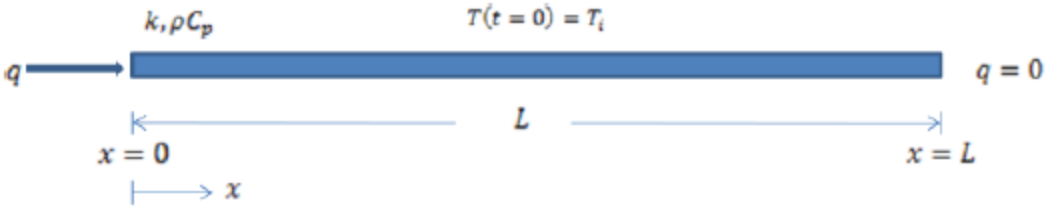
Example of variability-based integration bounds

Bootstrap method



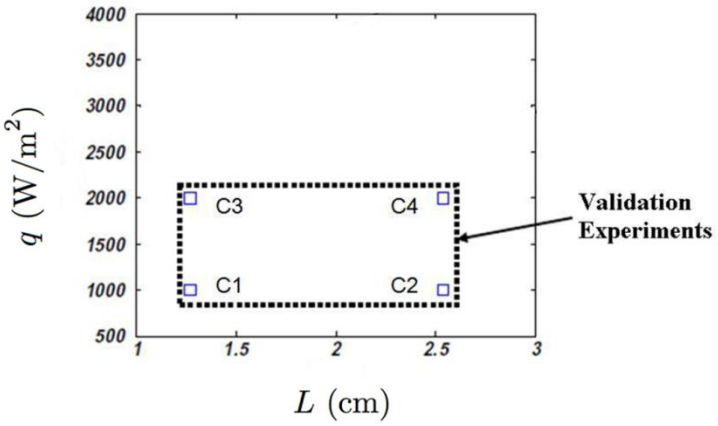
- Distribution-free
- Ease of implementation
- Proven asymptotic accuracy of inference
- Can handle non-i.i.d. data
- Can handle small sample size

Sandia thermal benchmark



Test

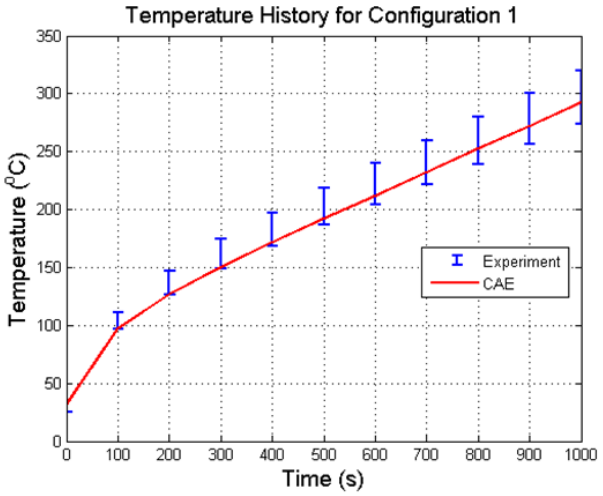
CAE

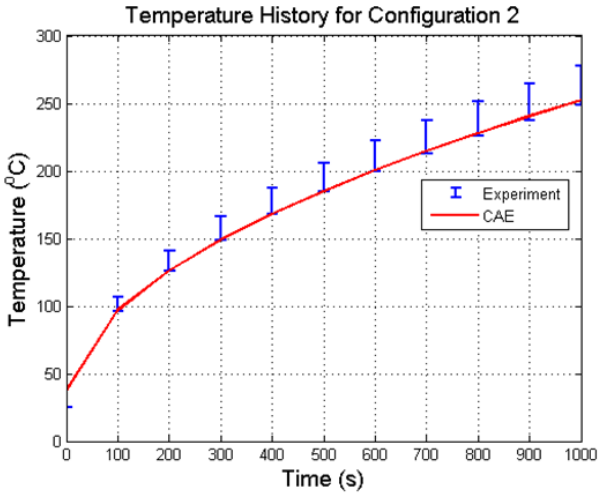


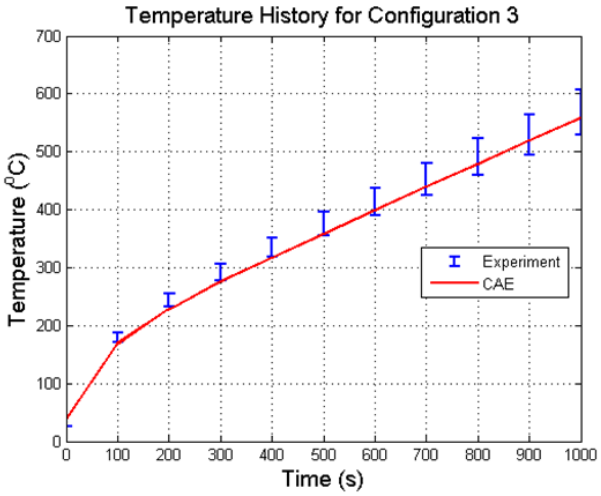
$$T(x,t) = T_0 + \frac{qL}{\kappa}\left[\frac{1}{3} - \frac{x}{L} + \frac{1}{2}\left(\frac{x}{L}\right)^2\right] + \frac{qL}{\kappa}\left[\left(\frac{\kappa}{\rho C_p L^2}\right)t - \frac{2}{\pi^2}\sum_{j=1}^{6}\left(\frac{1}{j^2}\exp\left[-j^2\pi^2\left(\frac{\kappa}{\rho C_p L^2}\right)t\right]cos\left(j\pi\frac{x}{l}\right)\right)\right]$$

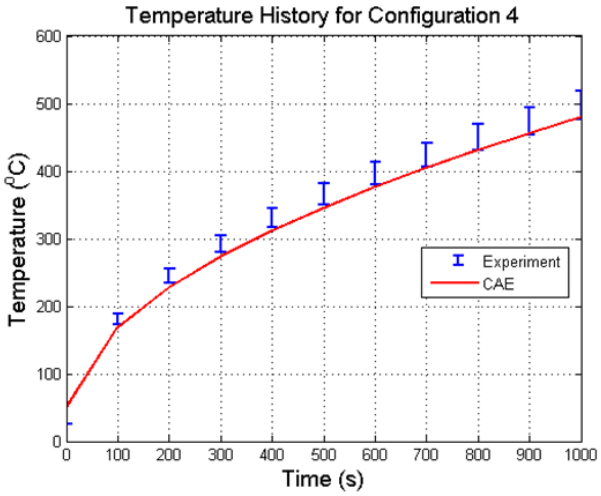
K. J. Dowding *et al.*, "Formulation of the thermal problem," *CMAME* (2008)

Validation data

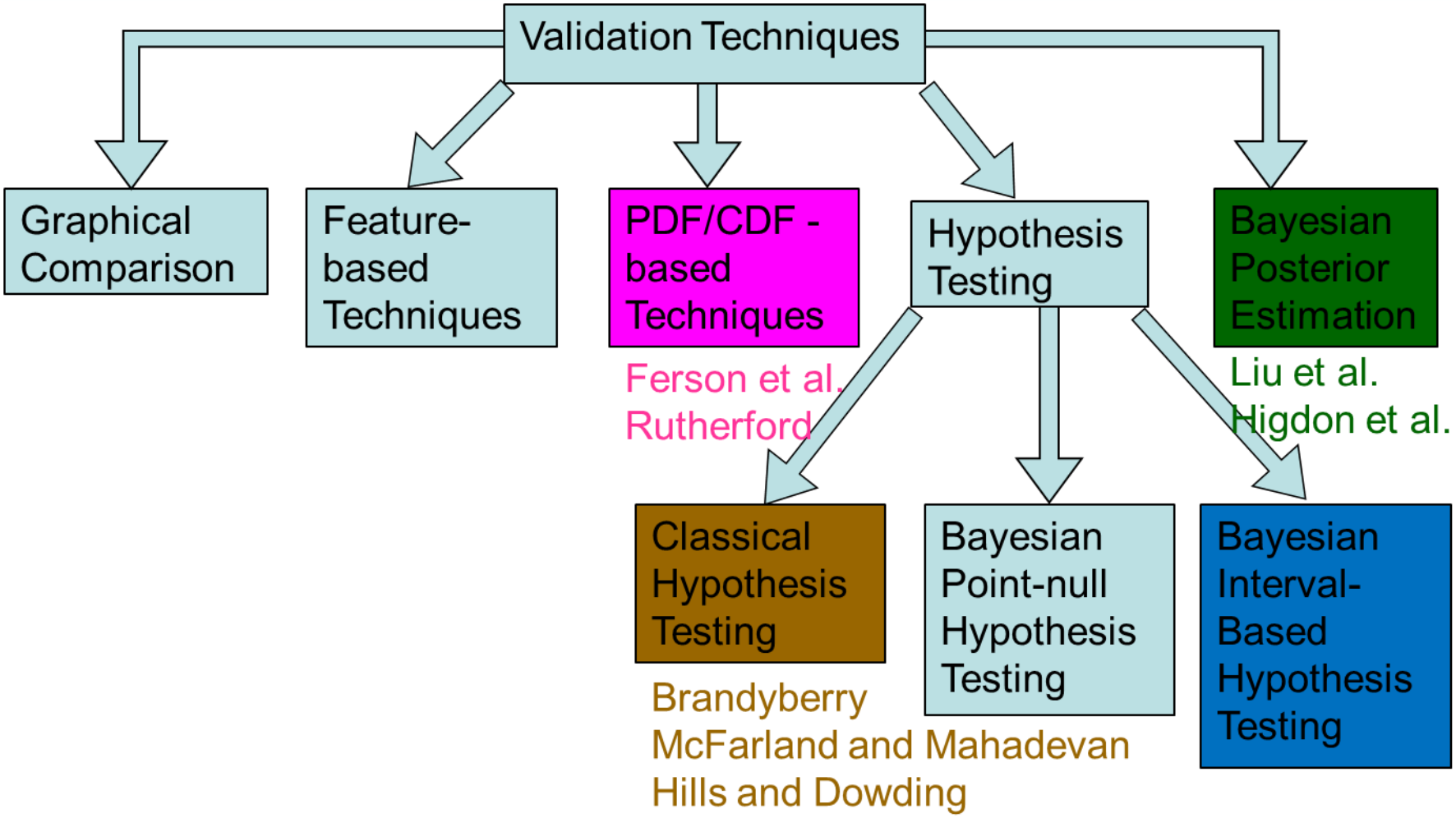




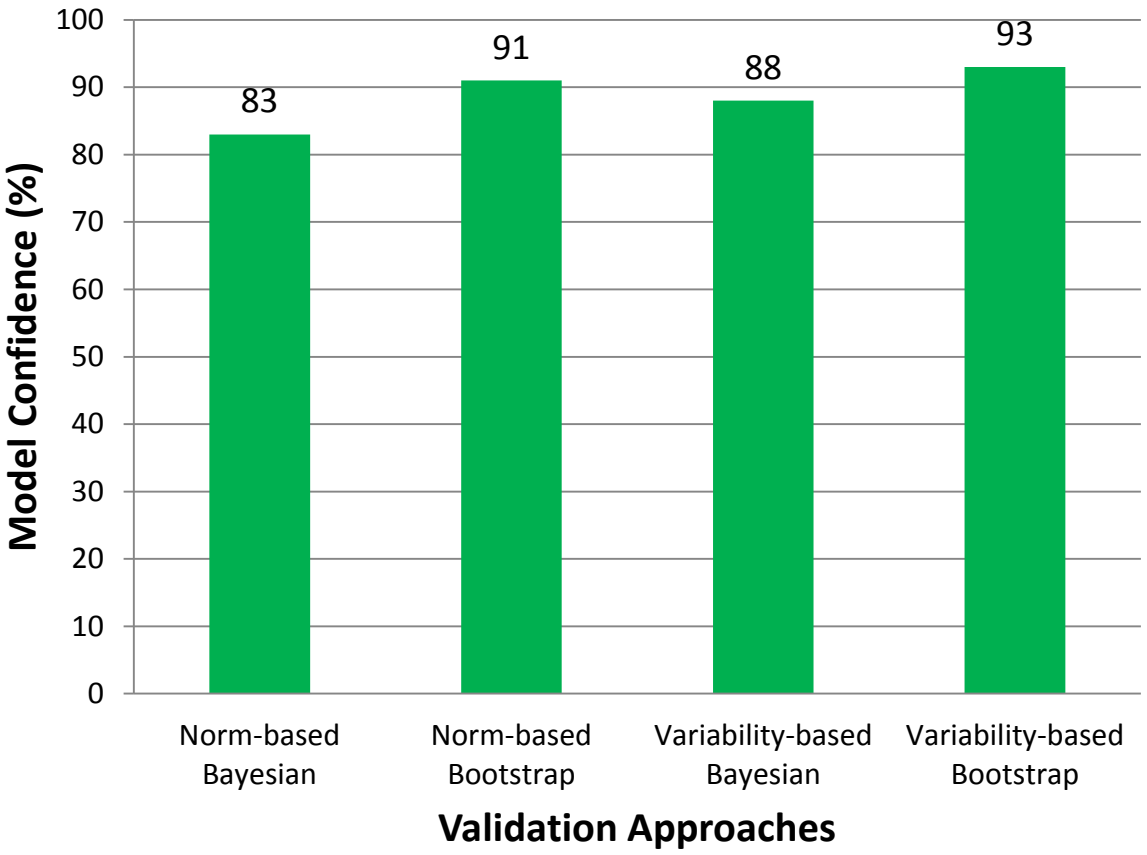




Validation studies



Validation assessment



Liu *et al.*	Negligible bias
Ferson *et al.*	Mismatch
Higdon *et al.*	Small discrepancy
Hills and Dowding	Poor
McFarland and Mahadevan	Valid
Brandyberry	Equivalent means
Rutherford	Inadequate

Reject

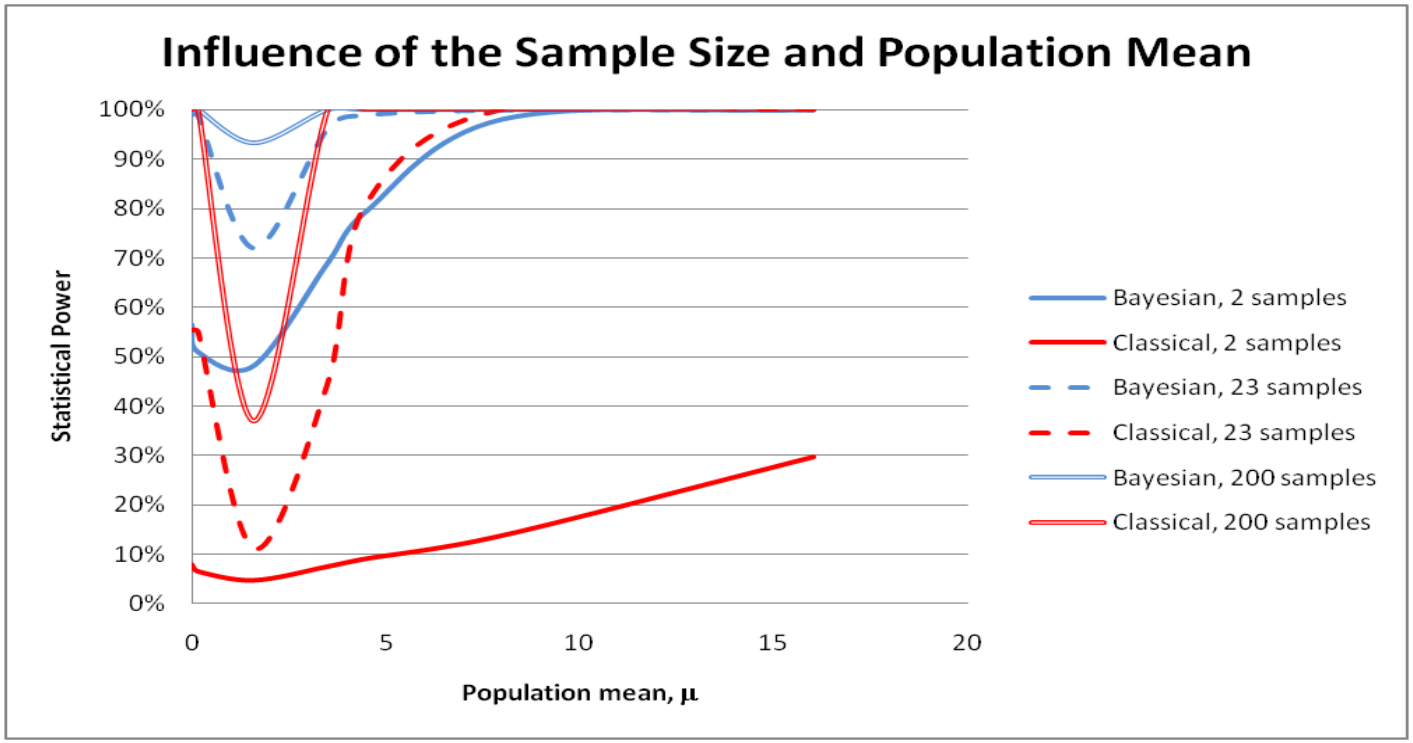
Accept

Statistical power

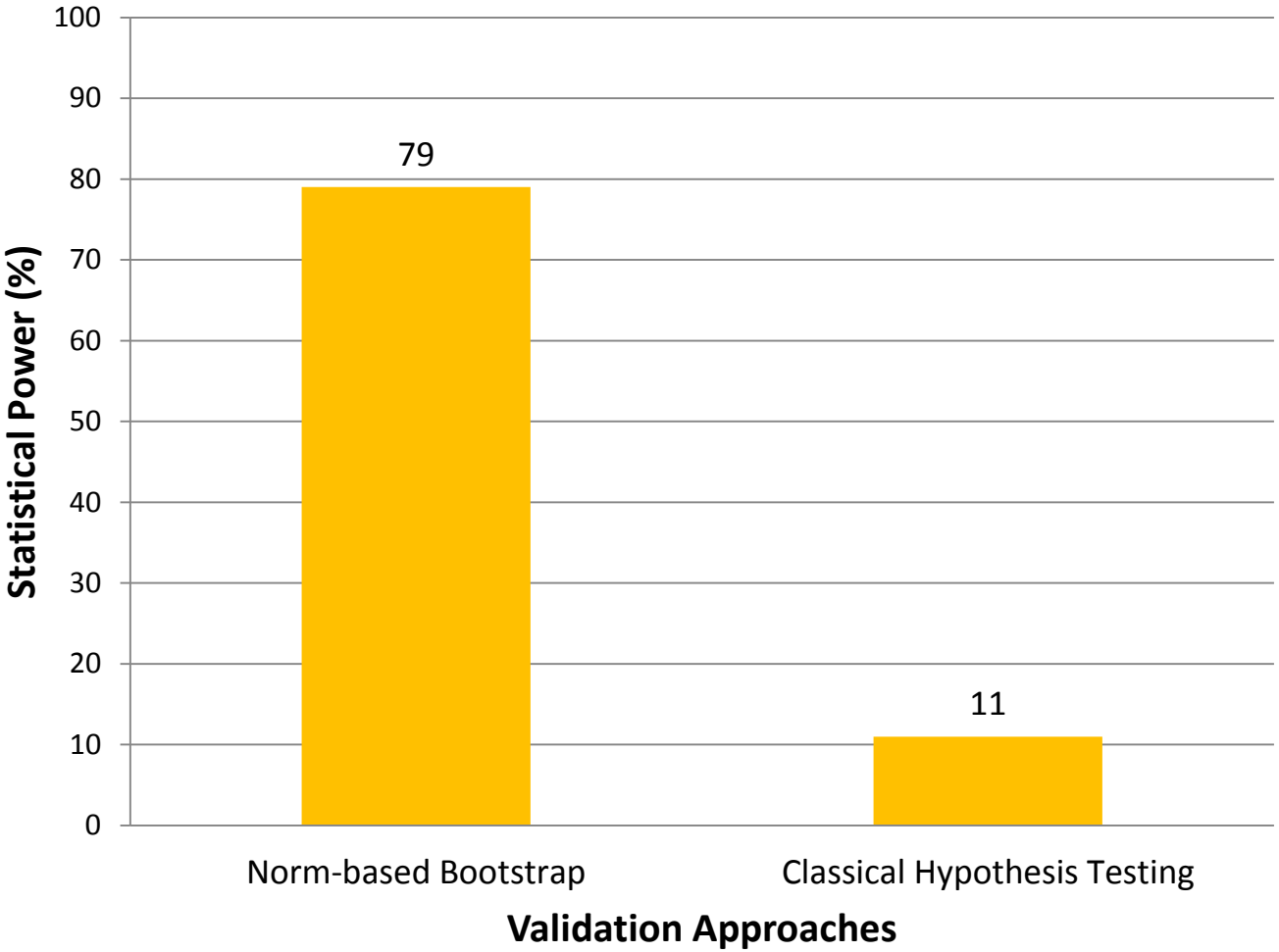
- Statistical power is the probability of rejecting the null hypothesis when it is correct
- Size of a statistical sample is the number of data points in a time series
- ε is the interval threshold used in Bayesian hypothesis testing
- μ is the population mean in the hypothesis testing H_0: $|\mu| < \varepsilon$; H_a: $|\mu| > \varepsilon$

Factors that influence statistical power

- Sample size
- Distance between population mean and epsilon
- Hypothesis testing type

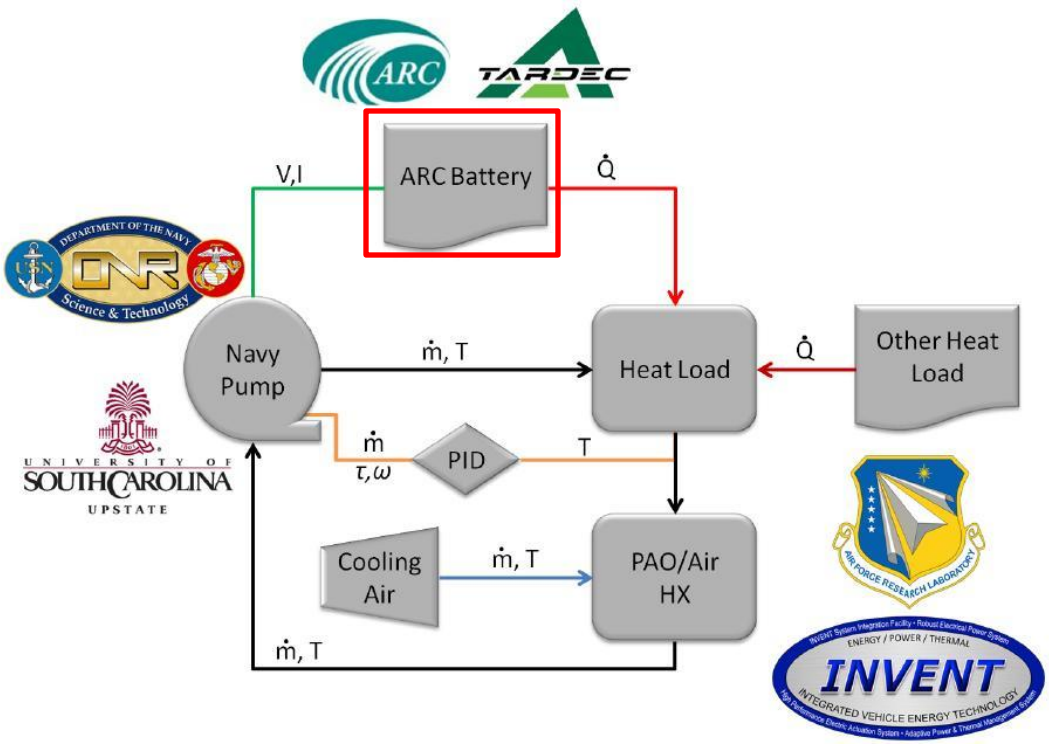


Comparison of statistical power



- Energy and Power Technology Community of Interest (E/P CoI) formed 2009
  - Couple technology to warfighter opportunity areas
  - Focus on developing and evaluating methods, tools and best practice guidelines for:
    - Model development, model sharing and documentation
    - Verification, Validation and Accreditation (VV&A)
  - Members include:
    - Air Force Research Laboratory
    - Electric Ship Research and Development Consortium (Florida State University)
    - Automotive Research Center (University of Michigan)

Battery model

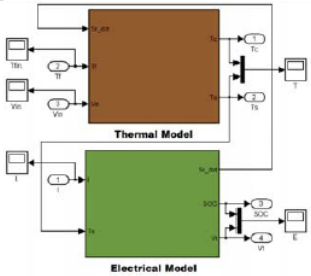


- Testbed for E/P CoI activities: straw-man model
- Battery model incorporated
- First step toward validating the straw-man model: validate the battery model
- Ultimately: provide validation metric, guidelines and tool

X. Lin et al, “Online Parameterization of Lumped Thermal Dynamics in Cylindrical Lithium Ion Batteries for Core Temperature Estimation and Health Monitoring”, IEEE Transactions on Control System Technology, under review

Validation results

Single Cell – ElectroThermal Model



- **Inputs**
  - I (Current)
  - Tf (Inlet Air Temp)
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- **Outputs**
  - Tc (Core Temperature (ºC))
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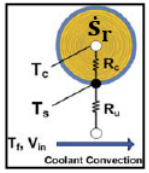
- **Thermal Model**
  - Two States (Tc, Ts)
  - Two Inputs (Tf, Vin)



[5] C. Park, et. al. 2003
[6] X. Lin, et. al. 2011
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- **Electrical Model: OCV-R-RC**
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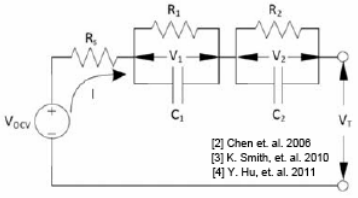

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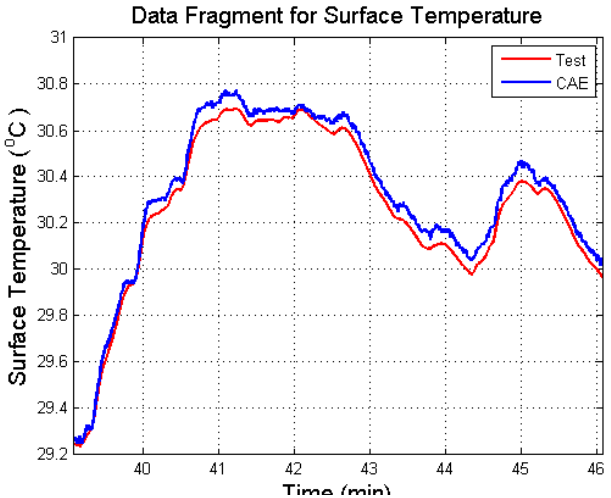
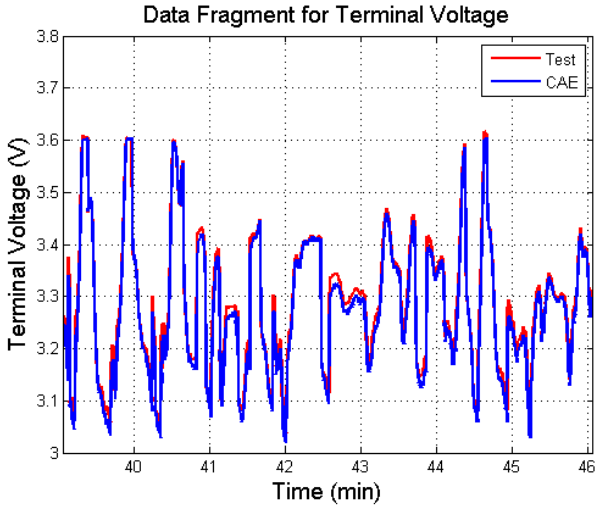




- Model Confidence is high (99%)

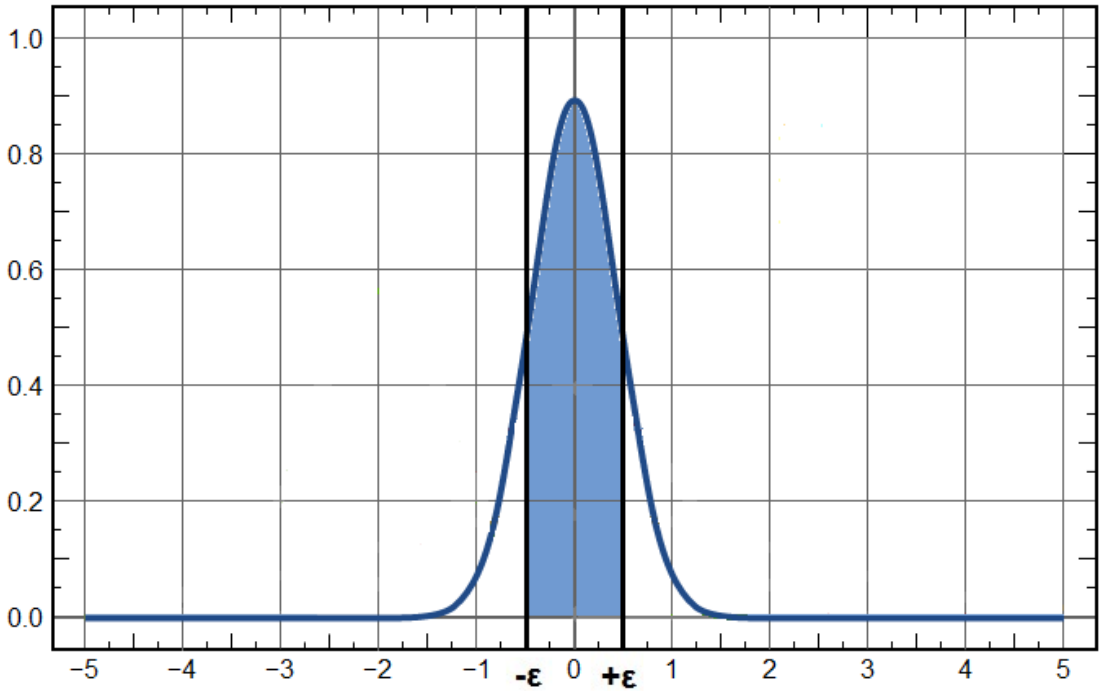
Contributors

- US Army TARDEC
  - David Lamb
  - David Gorsich
  - Mark Brudnak
  - Mike Pozolo
- Ford Motor Company
  - Yan Fu
  - James Zhan
  - Ren-Jye Yang
  - Saeed Barbat

Backup

Confidence quantification

Hypothesis test:
$H_o: |\mu| \leq \varepsilon$ (accept) *versus* $H_a: |\mu| > \varepsilon$ (reject)



$\bar{r}_d$: mean of r_d
n: number of observations
σ^2: variance of r_d

$r_d|\mu \sim N(\mu, \Sigma)$

$$K = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} exp\left[-\frac{n+1}{2\sigma^2}\left(\mu - \frac{n}{n+1}\bar{r}_d\right)^2\right] d\mu$$